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A PRECISION POINTING CONTROL SYSTEM FOR THE SPACE INFRARED TELESCOPE FACILITY(SIRTF)

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The SIRTF telescope carries on-board imaging, spectroscopy, and photometry instrumentation to investigate fundamental questions about the early universe, formation and evolution of galaxies, and formation of planetary systems, based on infrared astronomical observations. In order to meet stringent science objectives, the Pointing Control System (PCS) must achieve sub-arcsecond pointing accuracy and stability over exposure times in excess of 500 seconds. Requirements are complicated by the use of canning instruments that must be coordinated with PCS mapping maneuvers, in addition to the use of spectrographs requiring the stable placement of poorly known IR objects in the center of narrow slits. Constraints on size, cost and weight of the space telescope impose additional engineering challenges, and demand the effective use of integrated modeling, analysis, simulation, and control design tools.

Introduction

The Space InfraRed Telescope Facility (SIRTF) is the next and final component of NASA's Great Observatory program, following the Hubble Space Telescope (HST), the Advanced X-ray Astrophysics Facility (AXAF), and the Gamma Ray Observatory (GRO). The cryogenically cooled SIRTF telescope leverages recent breakthroughs in infrared detector array technology and a solar orbit, to ensure for the first time, astronomical observations that are not hindered by detector limitations or local thermal emissions.

The Space Infrared Telescope Facility (SIRTF) will be a one-meter-class (85 cm), cryogenically cooled, astronomical observatory currently planned for launch around the year 2001. The SIRTF candidate design has undergone substantial changes including a new solar orbit and design modifications that reduce the development cost by more than seventy-five percent while retaining much of the fundamental scientific importance and promise of the original SIRTF. The mission life for the new concept has been reduced from 5 to 2.5 years, and will be launched into solar orbit instead of the high earth orbit (HEO). These ideas have unabled a mass reduction of more than 70%. The biggest changes in the pointing and control subsystem (PCS) concept is the removal of the fine guidance function from the cryogenic telescope focal plane. The new concept mounts the external fine guidance sensor on the cryostat outer shell and is supplemented by a simple Pointing Control and Reference Sensor (PCRS) within the instrument chamber for periodic internal to external alignment calibration and precision repositioning of the telescope line of sight.

An integrated team consisting of JPL, Ball Aerospace and Lockheed-Martin Corporation (LMC) began phase-B implementation of the SIRTF mission, Lockheed-Martin will have the primary responsibility for the spacecraft development. The descriptions of the observatory and the PCS given here represent the current design concepts. The final design is under development by the Pointing Control Subsystem (PCS) Integrated Product Development Team (IPDT) under the leadership of LMC.

This paper discusses the SIRTF mission objectives, the science payloads, the pointing requirements, and presents a preliminary PCS design concept. The science payloads consist of the InfraRed Array Camera (IRAC), the InfraRed Spectrograph (IRS), and the Multiband Imaging Photometer for SIRTF (MIPS). Pointing requirements are outlined to support each of the instruments. Special attention is given to the IRS, since the pointing requirements needed to support high-quality space spectroscopy are significantly different from those imposed by imaging-type instruments, and drive many important PCS design considerations.

A strawman PCS design is presented along with the results from several simulation runs to demonstrate that the pointing requirements can be met with realistic (although not necessarily off-the-shelf) hardware. Various trade-offs and considerations in developing the requirements and strawman design are discussed, as well as future plans for building the final space telescope with joint NASA-industry participation.

Science Objectives

SIRTF operating outside the earth's atmosphere will obtain infrared observations that will enable scientists to:'

- Investigate the formation and evolution of galaxies, looking back in time into the early history of the universe.
- Study in detail young and forming stars and their interactions with their enveloping clouds of dust and gas.
- Study the chemical synthesis of the elements in supernovae in galaxies over 50 million light years away.
- Search for brown dwarfs that may constitute the missing mass whose gravitational influence is known, though no direct evidence of the "dark matter" has been found yet.
- Examine the fossil records of our solar system from the spectra of small cool bodies such as comets, asteroids and planetary satellites.
- Study the formation and evolution of other solar systems.

Science Payload

Three science instruments are being developed to operate in a cryogenic environment at about 1.5 Kelvins. This environment is required to obtain the low instrument and telescope thermal radiation backgrounds necessary to detect faint astronomical signals.

The Infrared Array Camera (IRAC) is being designed to provide imaging and polarimetry over the wavelength range of 1.8 to 27 micrometers,. This instrument is being developed at the Smithsonian Astrophysical Observatory.

The Infrared Spectrograph (IRS) is being designed to take medium resolution spectra of astrophysical targets, over the wavelength range of 4 to 200 micrometers. This instrument is being developed at Cornell University.

The Multiband Imaging Photometer for SIRTF (MIPS) will provide imaging, polarimetry, and large area mapping capabilities over the wavelength range of 40 to 200 micrometers. This instrument is being developed at the University of Arizona.

Mission Overview

The mission concept[3] is to launch SIRTF with just enough energy to escape Earth's gravity into a heliocentric orbit (hereafter referred to as a "solar orbit") with a small drift rate of about 0.1 AU per year away from the earth. The solar orbit was chosen over the previous HEO of 100,000 km altitude because it requires much less launch energy. The Delta launch vehicle, being considered for use with SIRTF, can place about 1000 kg into solar orbit. Other advantages of the solar orbit are: the reduced cryogen usage because the thermal load from the earth is greatly reduced, the Earth/Moon avoidance constraint is removed and the pointing and fault protection functions are simplified because of the more benign and stable thermal environment.

Figure 1, from reference 3, shows the solar orbit in a rotating frame relative to the Sun-Earth line. The SIRTF solar orbit is more eccentric than the Earth orbit and consequently the observatory appears to move towards the Earth at perigee and away from the Earth at apogee. Approximately 15% of the sky requires off-sun pointing, where the batteries are needed to supplement the solar panel power. Complete sky coverage is attained over the course of one year.

Pointing Requirements

Pointing Accuracy

The observatory is required to be capable of directing the telescope line of sight (LOS), to a science target, referred to by its coordinates in the J2000 system, to within 5 arcsecond (1σ radial). SIRTF has interpreted the (1σ radial) to mean that the actual LOS vector will lie within a cone of 5 arcseconds about the commanded direction with an associated probability of 68%. The roll angle accuracy has not been specified but it will be derived from other requirements.

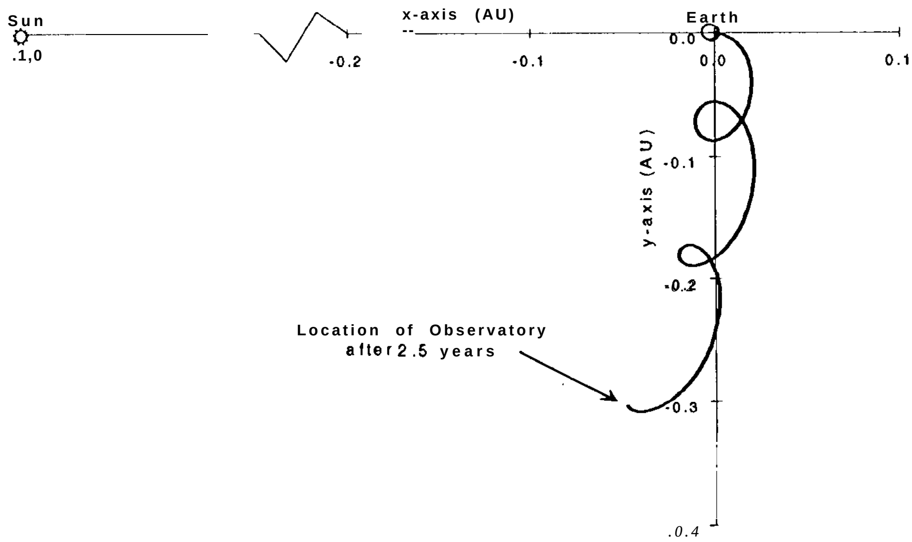

Figure 1- SIRTF solar orbit

Reposition (Relative) Accuracy

The IRS at the shorter wavelengths requires a pointing accuracy of 1/12th of the slit width, 0.4 arcsecond (10 radial), to reliably place a point source on the small spectrograph slit. Rather than levying such a high accuracy on the facility, a two-step positioning scheme has been devised. If the target position is known, PCS first places a known neighboring reference target on the Pointing Calibration & Reference Sensor (PCRS), with the 5 arcseconds accuracy. The second PCS step repositions the line-of-sight (LOS) in such a way so as to place the desired target on the slit with a 0.4 arcseconds relative accuracy. Therefore, this approach levies a 0.4 arcsecond relative motion requirement on the PCS without tightening the absolute knowledge requirement. The repositioning motion is limited to 30 arcminutes or less.

For the poorly known targets, the IRS instrument itself is employed to assist in the fine pointing. In the first step the PCS is required to place the target with an accuracy of 5 arcsecond on a specific IRS detector. The IRS instrument is then responsible for identifying the target and determining the offset required to place it in the center of the selected slit. This process is known as peak-up. The second PCS step repositions the line-of-sight (LOS) to within 0.4 arcsecond of the offset specified by the IRS peak-up detector.

Peak-up is necessary not only to relieve the facility pointing requirement, but also because:

- There are regions where there is uncertainty in target coordinates.
- Newly found comets and asteroids may not have ephemerides better than a few arcseconds.

In addition in some of the mapping functions, precise relative positioning of individual observations is required. Individual exposures are then stitched together into a map. The center-to-center spacings may be as small as 1.2 arcsecond with an accuracy of 0.4 arcsecond. This is the same requirement as the offset requirement needed to support the peak-up mode.

Pointing Stability

Pointing stability is a measure of the observatory jitter and directly effects the image quality, because it extends the point spread function over a larger area, blurring the image. SIRTF is required to provide image quality such that 50% of the light from a point source is enclosed within 2 arcsecond diameter circle at 3.5 pm. To be compatible with this performance, the PCS is required to maintain a stability of 0.6 (0.3) arcsecond over a 500 (200) second interval. The time interval is a compromise, long to provide depth in sensitivity but not so long as to unduly stress the PCS design.

Open-Loop Tracking

A tracking capability is required for observing solar system objects. The pointing accuracy and stability must be maintained during tracking for rates up to 0.21 arcsecond per second. This rate, which matches the rate of Halley's comet at a distance of 1 AU, is thought to be sufficient to cover most solar system objects. It is assumed that the ephemerides of many targets are known accurately to allow open loop tracking.

Coverage

SIRTF is required to have greater than 99.5% (95%) probability of acquiring any science target of interest over the region of (entire) celestial sphere within 60 degrees of latitude. It is assumed that the Tycho guide star catalog will be available for SIRTF. This provides a data base of over 1,000,000 stars down to magnitude 11 with an accuracy of 0.03 arcsecond and proper motion accurate to 0.03 arcsecond/year for the SIRTF mission time frame. The onboard catalog will be sufficiently large to ensure availability of four stars within the 30 X3° star tracker FOV..

Reconstruction

The absolute ground reconstructed pointing knowledge is required to be within 0.7 arcsecond (10, radial) relative to field astrometric stars. This accuracy is chosen to allow comparison with data at other wavelengths and from different instruments.

Maneuvers

The slew and settle time requirements are tabulated in Figure 2.

SLEW ANGLE	SLEW/SETTLE TIME (Seconds)
1′	20
7′	42
1°	100
5°	205
180°	820

Figure 2. Slew and Settle Time Requirements for SIRTF.

Pointing Control Subsystem Desire

The Pointing Control Subsystem (PCS) provides hardware and on-board software necessary to control, stabilize and determine spacecraft and instrument pointing. In addition to the instrument pointing functions described below, the PCS maintains solar array pointed to the Sun, and points the High Gain Antenna toward Earth when required. It provides the capability required for rapid large angle slews to place science targets within the instrument fields of view, or to point High Gain Antenna toward Earth for downlink. The PCS also provides the capability to ensure that pointing constraints are not violated and to place the Observatory in a safe-mode, in case of failure. The various operations of the subsystem can be grouped into the following PCS Pointing Modes:

- -Initial Rate Reduction, Acquisition and Initialization
- -Science Pointing
- -Slewing
- -Pointing Calibration
- -Momentum Management
- -Safe Hold

The Science Pointing Mode may be further subdivided into four observational pointing modes, according to the different types of Observatory motions required for the science observations. These can be summarized as follows:

a) Inertial-Pointing. This mode is used to perform long integration on faint objects. In this mode the line of sight (LOS) of the observatory is pointed to a desired J2000 direction and held inertially fixed for a period of time, (typically 10-500 seconds) to the following stability levels:

0.3 arcsec 1-o radial rms[a] over 200 seconds
0.6 arcsec 1-o radial rms over 500 seconds

[a] All pointing requirements stated as "1 $-\sigma$ radial rms" have been interpreted as equivalent to the rms of two equal un-correlated single axis gaussian error sources. Therefore, the corresponding "per-axis" pointing requirements are calculated as 0.707 of the "radial" requirement.

Depending on the instrument and the type of observation, two levels of absolute accuracy will be required:

Coarse Mode:

absolute pointing accuracy 5 arcsec 1-0 radial rms.
The coarse pointing mode is used to reliably place science objects on the larger format imaging detectors or within the acquisition range of other sensors (Peak Up Array, PCRS).

Fine Mode:

absolute pointing accuracy of 0.4 arcsec 1- σ radial rms.
The fine pointing mode is used to place science objects with well known positions on narrow instrument slits

b) Incremental Pointing Mode: In this mode the PCS performs small precisely controlled re-positioning of the LOS with an incremental accuracy (commendable resolution) of 0.4 arcsec, 1-o radial rms (across angular distances of up to **30 arcmin**). This Incremental Pointing' Mode is used to accomplish super-resolution and to move science targets within the focal plane. The incremental mode is also used to support the IRS instrument "Peak-Up Instruments" in which incremental pointing requests from the IRS are executed by the PCS as part of a target acquisition process that involves IRS Peak-Up Array measurements and pointing offset calculations. This strategy is used to acquire science targets (i.e., IRAS objects) whose a-priori position uncertainty is large (5 to 10 arcsec).

c) Scan Map Mode: In this mode, the PCS slews the observatory at a selectable constant rate of 2, 6, or 20 arcsec/s, while the MIPS scan mirror performs a matching saw tooth counter scan to "freeze" the image on the MIPS focal plane. This mode is used to efficiently map large (≈ 10 square degrees) areas of the sky. The combined Scan Mirror and PCS accuracies must be such that:

1. At the scan rate of 6 arc see/s there is no more that 0.7 arcsec rms image motion on the detector in ***5 sec*** (image smear requirement)
2. over 50s there is no more than 1 arcsec rms image motion (blind co-adding requirement)

d) Tracking Mode In this mode, the PCS slews the LOS to follow a ground generated pre-computed time-tagged profile at rates of up to 0.1 arcsec/s, to perform tracking of solar system objects.

Pointing Reconstruction

In addition to the above levels of on-board real-time pointing accuracy and stability, the PCS must also ***provide pointing knowledge*** of TBD (0,5) arcsec 1-6 radial in an rms sense, to support ***a posteriori ground pointing reconstruction*** requirement of 0.7 arcsec (in J2000), 1- σ radial in an rms sense. The currently stated goal for pointing reconstruction is to provide for each observation coordinates for every pixel with respect to J2000 within 0.7 arcsec rms radial. This goal will be addressed using a combination of PCS pointing knowledge and ground processing of PCS and science data. The final solution for pointing reconstruction will be a function of Observing mode (combination of telescope pointing and instrument mode). For example, analysis completed to date indicates that PCS data alone should be sufficient for inertial pointing observations while the MIPS scan map mode will require ground processing utilizing a combination of PCS and science data. The analysis completed to date has focused on the MIPS scan map mode since it was felt to be the most challenging case for pointing reconstruction. The approach analyzed, which should be capable of meeting the 0.7 arcsec reconstruction requirement at the 6 arcsec/s scan rate, involves the following ground processing steps: 1) blind co-adding is used to increase the number of detectable objects in the overlap regions; 2) centroiding on the objects detected in overlap regions is used to sew the scanned field of view together; and 3) centroiding on detected Tycho catalog objects to tie the mapped region to J2000.

PCS Implementation

To perform these functions, the PCS employs a celestial-inertial, three-axis stabilized control system. Attitude measurement, determination and reconstruction capabilities are provided by high performance (externally mounted) Star Tracker-Inertial Reference Unit (ST-IRU) package. All telescope pointing is defined and calibrated relative to redundant Pointing Calibration and Reference Sensors (PCRS), physically located in the focal plane inside the instrument chamber (for focal plane layout, see Figure 3). During the course of the mission the PCRS will be used to periodically calibrate out focal plane /external Star Tracker pointing misalignments that may arise from thermal/structural or any other s1ow1 y varying drifts. The Star Tracker/IRU package provides the primary sensing reference in the Coarse Pointing Mode. In the Fine Pointing Mode, the PCRS is used to initialize precision pointing offsets from nearby cataloged (Tycho) stars. Accurate execution of these offsets is then performed under precise IRU/Star Tracker control.

To achieve the required 0.4 arcsec relative accuracy in the Incremental Pointing Mode and to support the short term stability requirements, PCS requires the following IRU performance: Bias Instability better than 0.003°/hr over 8 hours, Angle Random Walk (ARW) about 10 μ-deg/√hr and resolution of 0.05 arcsec. For the Star Tracker, long term stability and the required reconstruction knowledge dictate that the SRU be capable of providing star position measurements accurate, in an absolute sense, to better than 1-σ per-axis/per-star of 1.5 arcsec (0.75 arcsec random) at the limiting 9^{th} visual magnitude at update rates of 1 Hz. The field of view of approximately 3° x 3° is driven by the need to insure coverage and maintain high accuracy (including a minimum of 4 stars at the galactic poles, to further improve measurement accuracy).

To achieve the 0.4 arcsec absolute accuracy required under the Fine Inertial Pointing Mode, the PCS employs the Pointing Calibration & Reference Sensor. The PCRS is a narrow FOV (-1 arcmin square) visible star sensor located in the focal plane. It is capable of measuring star positions with 1-c per-axis accuracy of 0.1 arcsecond at the limit of its 11 'h visual magnitude sensitivity, This sensitivity is related to the desire to use nearby Tycho objects. The Tycho catalog is complete to this limiting magnitude.

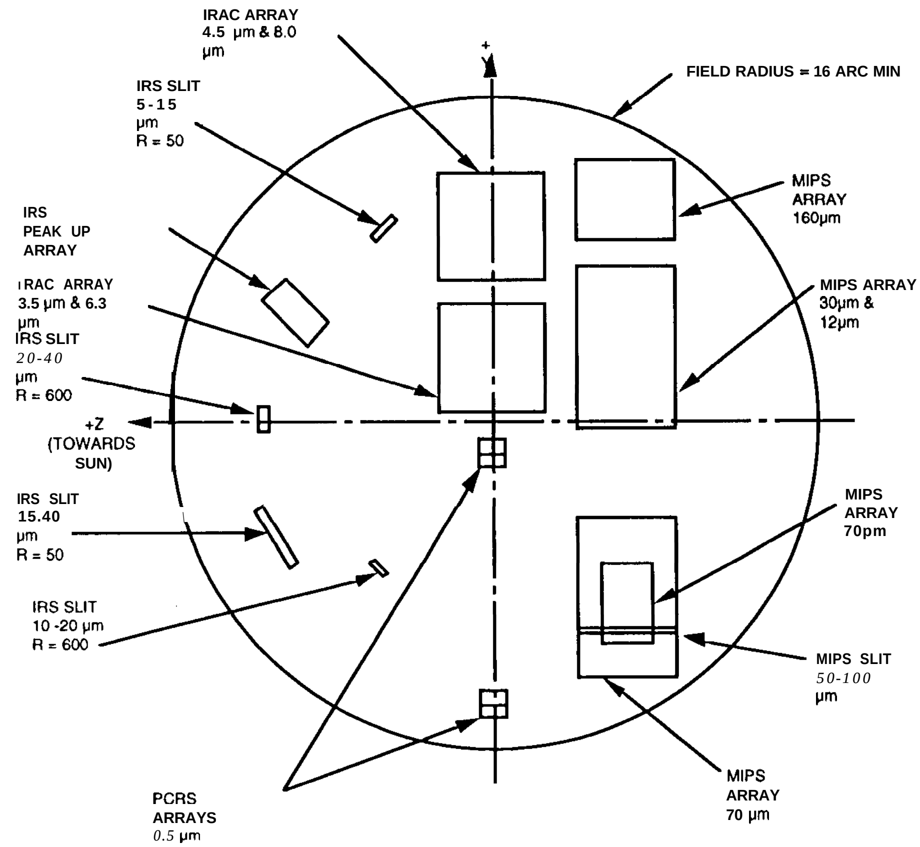

Figure 3 SIRTF focal plane layout.

Sun position with respect to the spacecraft is measured by a complement of externally mounted Fine and Coarse Sun Sensors. These sensors provide Sun position information to the on-board attitude determination function for initial acquisition as well as Sun avoidance, fault protection, and Safe Hold functions. Four reaction wheels provide the primary control actuation for all modes of operations. Reaction wheel sizing is driven by the need to provide sufficient capacity for quick repositioning, including moving 1 arcmin in less than 20 seconds, as well as large angle turns (180 degrees in less than 1000 seconds). The Reaction wheel is capable of providing torques in the 0.04-0.07 Nm range and storage capacity of approximately 20 Nms of momentum. A set of nitrogen thrusters (see Reaction Control Subsystem) provides the reaction wheel momentum unloading capability.

Attitude Control Simulation

Figure 4 depicts a block diagram of the SIRTF attitude control system. The control system uses standard 3-axis control with gyro and star tracker feedback.

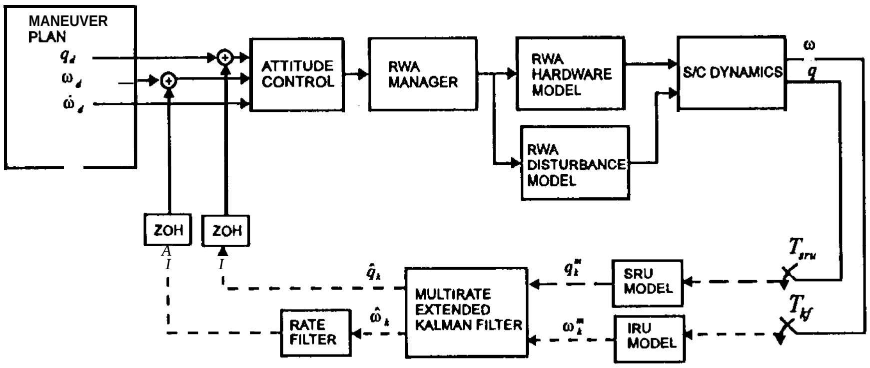

Figure 4: Attitude control block diagram

As a demonstration, the SIRTF telescope is slewed 30 arcmin about the Z axis. The resulting errors in each axis are shown in Fig. 5 as function of time, and the RMS error values are shown corresponding to the 300 second period between 100 and 400 seconds. It is seen that the control system has an approximate RMS stability of .07 arcsec in the Z axis over 300 seconds. This value assumes an optimal Kalman filter, which will by necessity be detuned in the final design to improve settling time and operations efficiency. The detuning of the KF is expected to degrade the indicated RMS values by a factor of 3 to 4 in the final design.

High Resolution Space Spectroscopy

SIRTF requirements for high resolution space spectroscopy are discussed below. A detailed signal diagram representing the spectroscopy requirements is shown in Fig. 6. The quantity w_0 represents the pointing process, which is assumed to be a second-order stationary Gaussian random process with mean w_b and variance σ_a^2. In pointing control language, w_b is defined as the bias and σ_a^2 is the long-term jitter, i.e., the RMS jitter associated with windows of infinite duration.

The pointing process W. is expressed in units of arceconds, and is defined with respect to the slit center. For example, if $w_0=0$ the image spot will be directly at the slit center. The fractional flux offset x(t,T) is defined as the amount that the actual flux deviates from the ideal case where the spot is held perfectly still in the center of the slit over the entire exposure of length T. To leading order, the flux deteriorates quadratically with offset of the target from the center of the slit. The coefficient A_2 captures this effect in a square-law flux profile, which is determined by fitting curves of fractional flux offset versus position. In this manner, the coefficient of A_2 is calculated as a function of slit geometry, wavelength, and the optical design[7], and has a worst case value of A_2 =.13 as^{-2}. for the SIRTF IRS. The pointing control objective is to keep the image spot in the center of the slit by keeping the smoothed flux offset x small. Specifically, for accurate measured line ratios, it is desired that the probability of x exceeding a specified threshold d be less than a specified probability α, i.e.,

$$x_{1-\alpha} \leq d$$

where $x_{1-\alpha}$ is the 1 -α percentile of the probability distribution of x(t,T). The exact percentile is hard to compute, so that the statistical percentile is typically replaced by an overbound in the analysis[4]. .For SIRTF spectrographs, it is desired that the 95th percentile (i.e., α =.05), of the flux offset be less that d=.07. This requirement is very different from requirements for imaging instruments that avoid smearing by constraining the allowable RMS jitter over a window of specified duration[6]. In contrast, the percentile requirement simultaneously constrains both the pointing bias and the jitter. As a result this pointing requirement is very stringent. For example, assuming that the bias and jitter components for SIRTF are the same, they must each be less than approximately .3 arcseconds RMS to satisfy the d=.07 flux offset requirement for short exposures. This translates into a very tight requirement on the absolute pointing accuracy. Because the star tracker bias alone can be larger this accuracy requirement, it becomes necessary to use precision offset maneuvers and a reconfigurable control scheme to support all spectroscopy science on the SIRTF telescope.

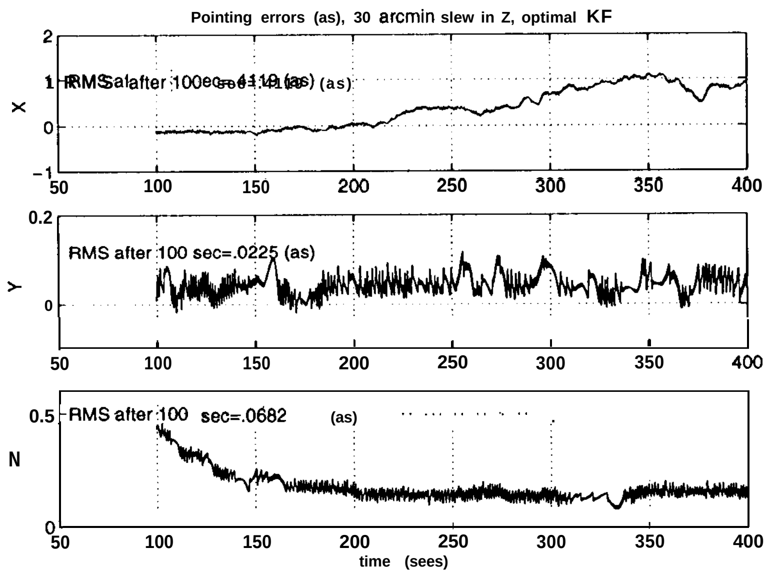

Figure 5: closed-loop pointing after 30 arcmin slew

Reconfigurable Control Architecture

It was seen that pointing requirements for high resolution spectroscopy are difficult to meet using standard 3-axis control because of the star tracker (and other systematic) biases. An alternative approach based on a reconfigurable controller has been proposed in and is discussed in this sections. The basic idea is to place the image spot into the slit using a precision incremental maneuver based purely on gyros, starting from an initial calibrated position. This avoids most of the bias error associated with the star tracker.

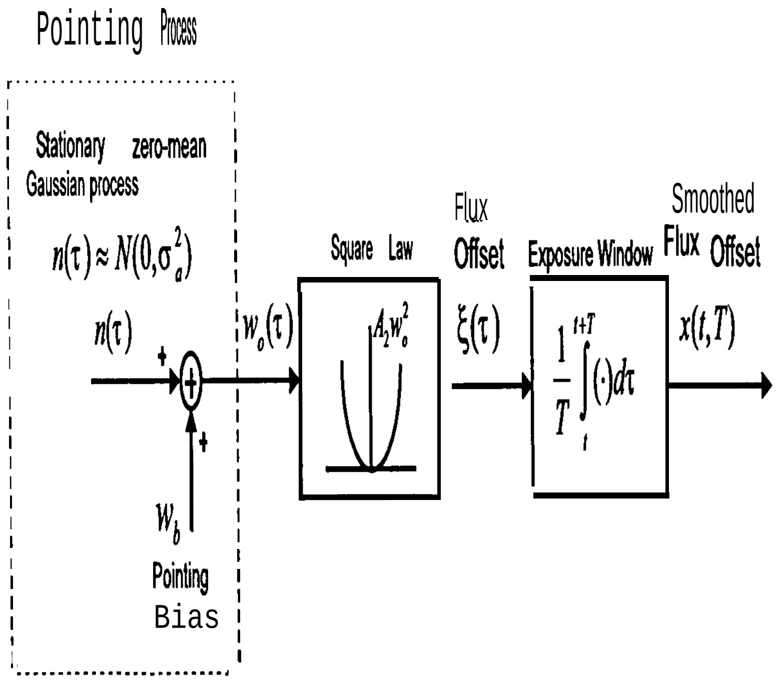

Figure 6: Signal diagram for spectroscopy pointing requirements

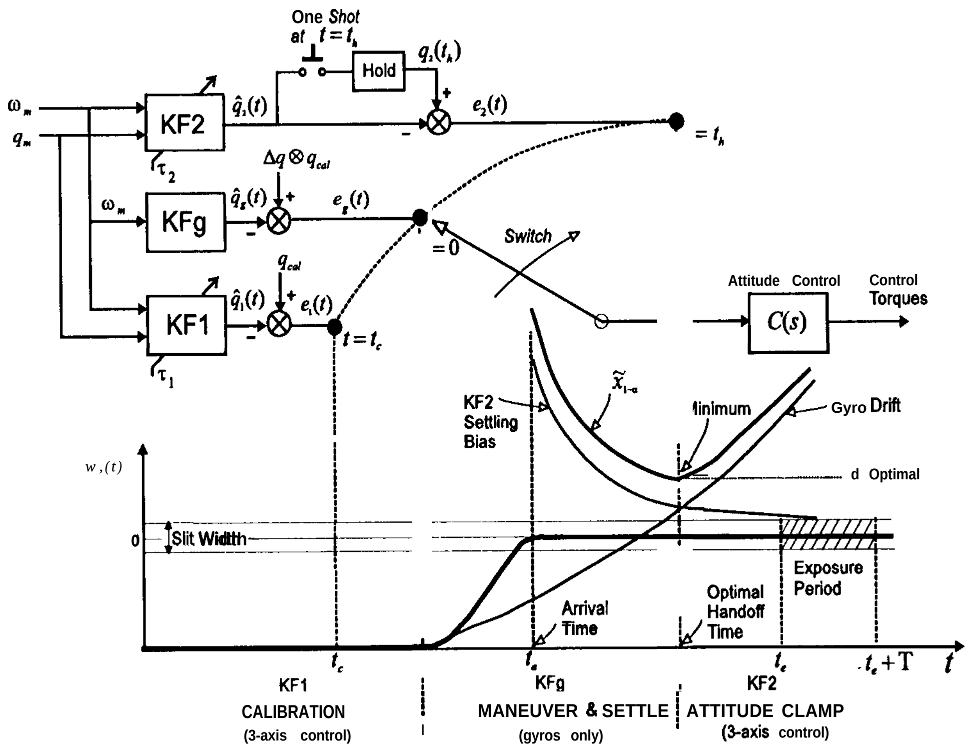

Figure 7: Reconfigurable control architecture for high-resolution spectroscopy

The proposed reconfigurable control architecture is shown in Fig. 7. Here, KF1 and KF2 are Kalman filters which have been detuned to have time constants τ_1 and τ_2, respectively. KF1 and KF2 are both driven by the measured position quaternion q_m and the measured 3-axis rate ω_m, while KFg is the optimal Kalman filter designed only with a rate measurement input. In this scheme, KF 1 and KF2 are free running filters, while KFg is initialized by KFl at time t=0.

As shown in Fig. 7., the error signal that drives the attitude controller is taken from KF1 at time $t=t_c$, and is switched to KFg at time t=O, and is switched to KF2 at time $t=t_h$. It is assumed that the telescope and star tracker are in different frames, and that the body frame corresponds to the star tracker frame. Details of the particular handoff sequence are given below,

1. point telescope to a calibration source at attitude q_{cal} by nulling the control error e_1 (t) associated with KF1.

2. Calibrate the frame misalignment between the tracker and telescope using a calibration source (as imaged on a detector in the telescope frame) during time interval $t_c < t < 0$ while holding attitude on KF1.

3. Calculate the incremental offset Aq in the body frame needed to put a target source into center of spectroscopy slit.

4. At time t=O, command the attitude Aq $\otimes q_{cal}$, and null the control error e_g (t) associated with KFg to implement maneuver.

5. Target arrives at slit at time $t_a > 0$.

6. At $t=t_h > t_a$ sample the "one-shot" to clamp the attitude estimate associated with KF2, and null the control error e,(t).

7. Hold attitude by nulling $e_2(t)$ until the spectroscopy exposure of duration T is completed.

It is emphasized that the attitude estimate from KF2 is clamped at time t_h to generate the control error $e_2(t)$ to be nulled. No effort is made to reconcile the estimate from KF2 with the estimate from KFg, since this would typically cause a large jump in the combined state estimate at time t_h (on the order of the tracker bias) which could kick the image spot out of the slit. In fact, this is the reason that standard 3-axis control fails, and is avoided in the reconfigurable control concept.

The reconfigurable control concept is applied to the SIRTF telescope in support of the IRS payload. For this example, an infrared target is maneuvered 30 arcminutes from the Peakup array to the spectroscopy slit.. The 95 percentile overbound is plotted in Fig. 8 for the values τ_1 = 10,20,30 and τ_2 = 10,20,30. It is seen that the percentile decreases initially (because of the settling of KF2), and then increases (because of gyro drift). Intuitively, if the hand-off is too soon, then there is penalty in the bias error because one will be clamping on a filter (i.e., KF2) which has not completely settled, However, if one waits too long, the gyros will have drifted excessively. Hence there is a natural optimal time for the handoff from Kfg to KF2 which appears as the minimum of each curve in Fig. 8. If the handoff is optimally timed to catch the minimum of each curve, it is seen that the desired value of d=.07 can be satisfied with any one of several possible designs. One reasonable design is τ_1 =72 =20 which requires optimal handoff at $t=t_a+30$ seconds, and achieves a performance better than d=.06. Without reconfiguration, the SIRTF 3-axis attitude controller for the same example would perform no better than d=. 15, and would have additional drift terms which have not been analyzed here. Hence the reconfigurable control approach is essential for meeting the requirements of high-resolution spectroscopy science on SIRTF.

Spectopy: Pointing Analysis

To verify adequacy of the requirements and sufficiency of the design, a few key science scenarios were analyzed. For each scenario, pointing error budgets and timelines was developed. The scenarios evaluated included MIPS mapping, MIPS super-resolution and the IRS spectroscopy. For the sake of brevity, only the IRS spectroscopy analysis will be discussed in this paper. The IRS spectroscopy required the two-step PCS operation mentioned previously. It also imposed the tightest requirement and requires the most innovative pointing approach.

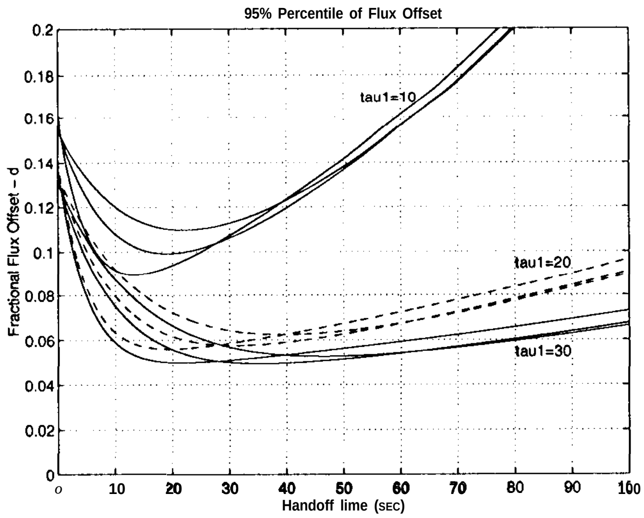

Figure 8: Optimal Handoff Timing and Performance

As mentioned before, the IRS spectroscopy requires that PCS places the target within 1/1 2 (0.4” 1-o radial) of the centerline of a particular slit. It further requires that the target remains within 1/8 (0.6” 1-o radial) of the initial position. Placement of the target is two-step process. Initially PCS places a well-known reference target, selected to be within 30’ of the desired target, on the PCRS array. PCS will then measure the reference target attitude, calibrates the frame misalignments between the star tracker and the facility LOS and calculates an offset angle for the second step. The process for the poorly known targets require an additional step. In that case, following calibration, PCS places the desired target on the IRS peak-up array. The IRS peak-up array would then calculate the final offset angle. The coarse pointing requirement" applies to all these steps. During this period PCS remains in its normal celestial-inertial control mode. The full complement of the Star trackers and Inertial Reference Units (IRU) maintains the desired pointing stability and absolute accuracy. However the selected pointing sensors could not support a 0.4' accuracy repositioning under the celestial-inertial control. It would however be possible to accomplish this feat on gyros only. Therefore, all precision small angle reposition maneuvers are performed under inertial control. Repositioning error budget is shown in Figure9.

The second phase of the IRS spectroscopy has its own set of difficulties. Although, it may be possible to remain in the inertial mode at the end point, the stability requirement over the extended desired observation period makes this approach impractical, The requirements on the stability necessitate transition back to the celestial-inertial control mode. The star tracker measurement at the completion of the turn provides the commanded attitude that the PCS would have to hold. However, since single measurement tracker performance is incompatible with the spectroscopy requirements, multiple measurements will be utilized to improve the measurement accuracy. This process reduces both bias and the random components of the measurement. This approach requires running a recursive attitude estimator in parallel, until the estimator converges to the desired level of performance. To improve on the observational efficiency, it would be possible to transition before the optimum time. Figure 10 provides the stability error budget for this mode. The PCS estimator error was calculated from the Kalman estimator steady state solution, which was derived by solving the Riccati equation.

$$\text{Cov (angle)} = s' = [2((A*\sigma^2/N)*N2^3)^{1/2} + (A*\sigma^2/N)*N1]^{1/2}$$

where,

N 1 is gyro angle random walk ($arcsec^2$/see),
N2 is gyro drift instability ($arcsec^2/sec^3$),
A is the star tracker integration period (seconds),
σ is the star tracker's random error (arcsec),
and N is the number of stars observed and identified.

SIRTF Implementation Plan.

SIRTF will be developed by an innovative JPL-Industry Integrated Design Team (IDT). IDT includes a JPL team, the science instrument principle investigators, and three industry teams with the prime responsibility for the development of the Cryo Telescope Assembly (CTA), the spacecraft and the integration and test teams, JPL selected Ball Corporation to lead the CTA and Lockheed-Martin Company (LMC) to lead the spacecraft development and the facility integration and test. Special Integrated Product Development Teams (IPDT) including members from all entities, have been formed to address each area of the development. PCS IPDT is one such team lead by LMC with members from JPL engineering and the science community. PCS IPDT will use the design described in this paper as a starting point but will not be bound by it. The PCS design will be finalized prior to SIRTF Preliminary Design Review (PDR), scheduled for October 1997.

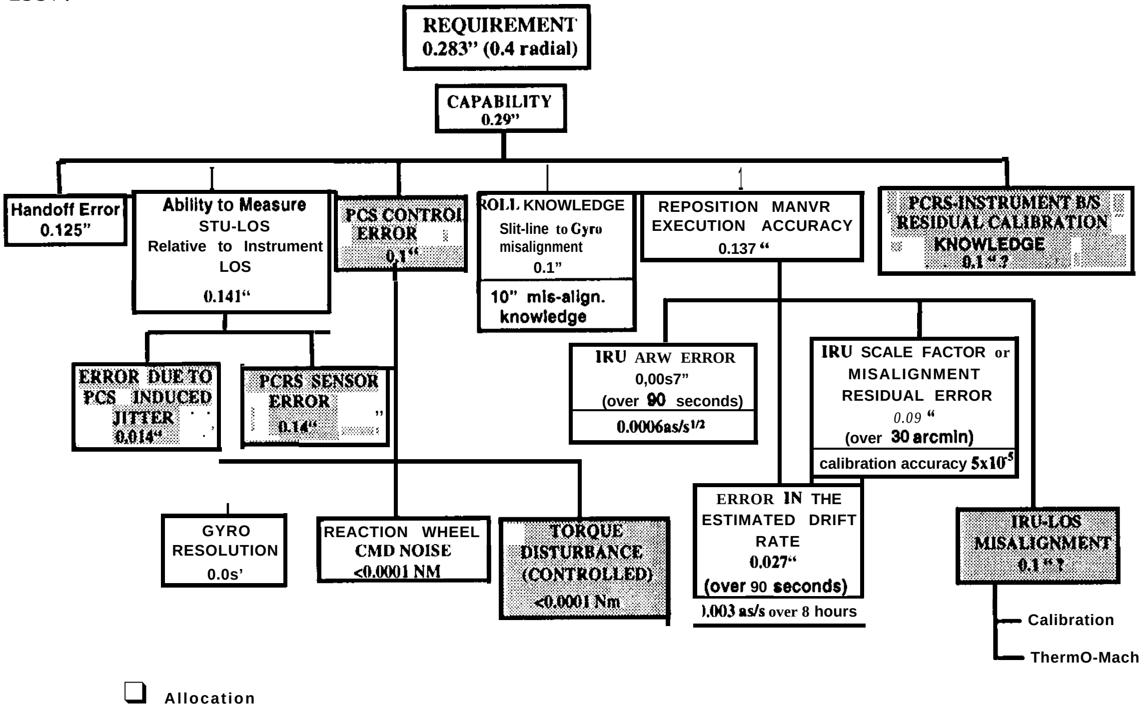

Figure 9. Repositioning Error Budget for 30 arcmin turn.

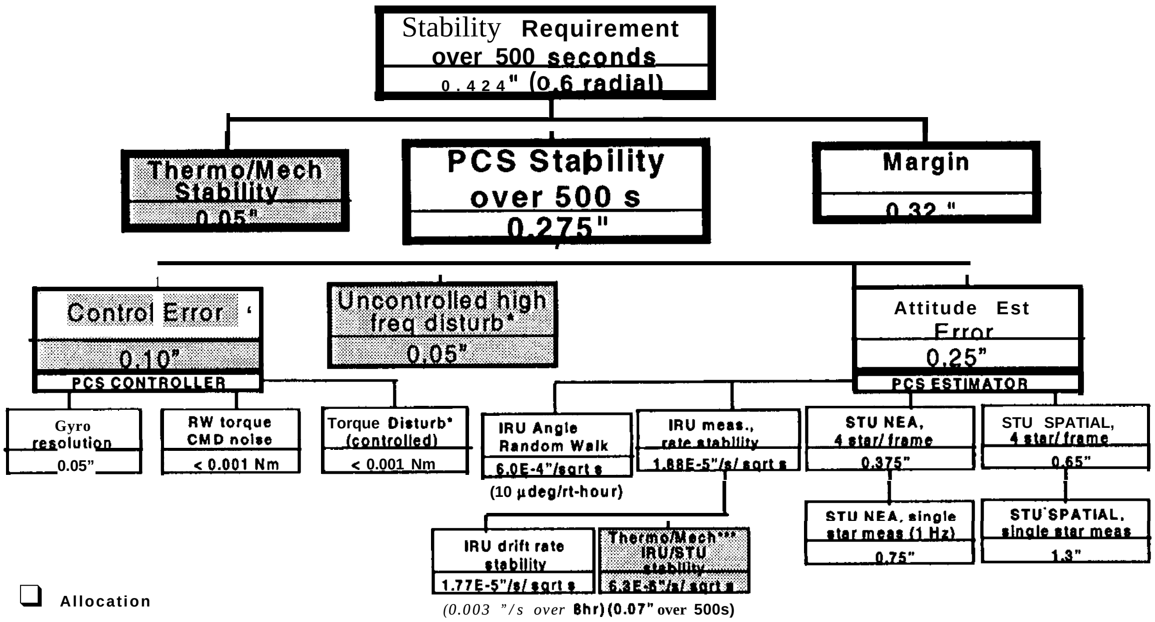

Figure 10. Stare Mode stability error budget.

Conclusions

Pointing and control requirements have been reviewed and a candidate design has been discussed for the SIRTF observatory. The performance driving requirements are: pointing knowledge to 5 arcsecond, stability to 0.6 arcsecond over 500 seconds' duration, relative repositioning to within 0.4 arcsecond and sky coverage of 99.5%. Basic features of the design include, an arcsecond class externally located tracker, a SKIRU class IRU and cold visible sensors for boresight and star tracker alignment. Key design feature is a reconfigurable control system allowing for smooth transitions between celestial-inertial and inertial control modes. The Reaction wheels are used for slew maneuvers and a cold gas system is used for momentum dumping,

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